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Evaluation of MAC Protocols with Wake-up Radio for Implantable Body Sensor Networks

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Abstract

The use of wireless communication in implantable medical devices is growing rapidly due to an increasing demand for sophisticated health-care. Recently, a new type of sensor network called Implantable Body Sensor Network (IBSN) has emerged. IBSN is a network of implantable medical sensors and devices which can communicate with each other or to a base station using radio-frequency (RF) link. Wireless communication in IBSN must be extremely reliable and energy-efficient in order to provide a long-term safe operability. The underlying MAC protocol in an RF communication is an important feature which directly affects reliability and energy-efficiency. To overcome the high power demand of wireless communication in IBSN, the concept of wake-up radio was introduced. Some MAC protocols that can make use of wake-up radio have been proposed. This paper analyzes three of the existing MAC protocols with the wake-up feature that are suitable for IBSN, and emphasizes their strengths and weaknesses. Simulations show that performance of MAC protocols with wake-up radio varies with different access mechanisms. Finally, we present an overview of MAC protocols with wake-up radio and discuss their practicality in implantable medical sensor networks.

Keywords: MAC protocols, body sensor networks, implantable medical devices, wake-up radio.

1. Introduction

The use of wireless sensor networks in the health-care industry is rapidly developing. Miniaturization of sensors [1], in-body data communication [2], and bio-compatibility [3] are the main topics of on-going extensive research. The in-body sensing of various life-critical physiological signals such as heart rate, blood pressure, blood-glucose level, and tremors is made possible with miniaturized implantable sensors. Numerous challenging requirements of health-care applications have resulted in a more specific type of medical cyber-physical system called the Implantable Body Sensor Network (IBSN), in which sensor nodes are implanted either subcutaneously or by invasive surgery into the patient's body and are connected to a body node coordinator using a wireless link. Life-critical implantable medical devices such as pace-makers, neural stimulators, and drug-delivery systems can be programmed dynamically based on the sensor readings through the wireless link. Less human intervention in measuring and programming these life critical medical devices will result in a reduction of human errors and hence more accurate care.

1.1. MAC protocols

One of the important challenges of IBSN is energy efficiency which also has some effect on reliable communication between the implantable sensor nodes. Medium Access Control (MAC) protocols directly affect the reliability and energy-efficiency features of wireless communication. Different MAC protocols that are aimed at Body Sensor Networks (BSN) such as BodyMAC [4], HEH-MAC [5], MEB-MAC [6], and ULP-MAC [7], using different access mechanisms such as Time Division Multiple Access (TDMA), Carrier Sense Multiple Access (CSMA), or Frequency Division Multiple Access (FDMA) have been proposed. In all these access mechanisms the wireless communication suffers from three main problems which affect the power consumption in order to increase the reliability: (1) *Idle listening* is the radio listening for packets while no packets are being sent. Idle listening in conventional CSMA-based MAC protocols is reduced with a specific back-off period. (2) *Overhearing* can occur when the radio is listening

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to packets which are not destined for it, which causes energy wastage in decoding such unwanted data packets. (3) *Packet collision* can occur when two nodes compete to transfer at the same time through the same channel. TDMA methods can overcome collision by assigning time slots for each node, which requires an accurate synchronization of time in the network. CSMA with collision avoidance may consume more energy in the back-off period. These problems need to be minimized for sophisticated implantable sensor nodes, as neither unreliability nor waste of energy can be tolerated in critical medical systems. A few MAC protocols have emerged which focus on the above issues; however, most of them do not address them in a single protocol.

1.2. Wake-up radio

In order to overcome the conventional MAC problems, a novel approach of using two different radio channels for ad-hoc networks was introduced by Signh et al. [8]. The idea of a separate out-of-band wake-up radio (WUR) used alongside the main radio in sensor networks was later introduced by Van der Doorn et al. [9], which operates with less energy than the idle-power of the main radio. This ensures that the power consumption of the main radio is greatly reduced, by putting the main radio to deep sleep mode. The major drawback of WUR is additional hardware overhead. However, several ultra-low-power WUR architectures have been proposed which can be embedded in the same chip area as that of the main radio [10] [11]. The Microsemi ZL701402 chip [12] has both a main radio operating in the Medical Implant Communication Service (MICS) radio frequency band and a 2.4 GHz WUR on the same chip. A 0.13 μm CMOS technology WUR with on-off keying modulation with a power consumption of 98 nW was presented by Roberts and Wentzloff [11]. Not many MAC protocols use WUR, but some of the protocols have been proposed in this regard in literature. Three of the protocols using WUR are analyzed in our paper.

1.3. Practicality of MAC protocols with WUR in IBSN

WUR typically introduces additional hardware, leading to energy overhead, performance overhead and chip-area overhead. With the advancement in nano-electronics and advanced chip-fabrication technologies, it is possible to have two radio transceivers operating at different frequency bands in a single chip package. Also, as shown in [11] a WUR with OOK modulation can operate in the nanowatt range. The practicality of MAC protocols with WUR in IBSN can be stated as the capability to communicate using dual-band radio transceivers implanted inside a human body with a bio-compatible package, meeting the requirements of different health-care services. For the hardware to be practical for the implementation in implants [1][2][13], a power-efficient yet performance-oriented control is required over the wireless medium. The power consumption and performance of MAC protocols with WUR are not traded off as it is in the case of normal MAC protocols.

This paper is organized as follows. In Section 2 related work is presented, followed by Section 3 in which an application scenario is explained for IBSNs and the MAC requirements are discussed. In Section 4, an analysis of WUR MAC protocols with three different access mechanisms is presented. In Section 5, simulation setup and results are presented. A final overview of results and discussion is provided in Section 6.

2. Related work

MAC protocols for BSN have been widely researched. There are many evaluation papers [14][15][16] and surveys [5][17] on MAC protocols for BSN that analyze the protocols mathematically as well as with real-world implementations. Gopalan and Parket [15] present a survey of energy-efficient MAC protocols for wireless BSN, evaluating the MAC protocols based on different access mechanisms. Ullah et al. [14] present an empirical analysis of MAC protocols for in-body and on-body sensor networks. Javaid et al. present a survey concluding that TDMA is the best access mechanism for wireless body area networks due to high throughput and minimum delay. Chin et al. [16] analyze power-efficient MAC protocols along with a system architecture for routing and security. Rahim et al. [18] provide a comprehensive survey of existing MAC protocols for BSN and conclude with open research issues for future work. Bradai et al. [17] present a performance analysis of MAC protocols for wireless BSN by simulating three MAC protocols with different access mechanisms. Lont et al. [19] have done a mathematical analysis for the power budget by comparing one of the WUR MAC protocols with two other low-power MAC protocols. The analysis of different WUR MAC protocols remains largely unexplored, in particular where implantable body sensor communication is concerned.

2.1. Motivation and Contribution

MAC protocols with WUR will benefit from the wake-up feature, overcoming the limitation of conventional MAC protocols and also providing energy-efficient operation. Our contribution, an analysis of existing MAC protocols with WUR with a specific channel model and application scenario, will facilitate optimization of these protocols and also open up further research directions. The comparison of MAC protocols with and without WUR will emphasize their strengths and weaknesses. Upon evaluation, the choice of a MAC protocol for a specific application scenario and standardizing the MAC protocol becomes easier.

We aim to contribute to this by presenting an overview of different MAC protocols featuring WUR that benefit in different aspects of a MAC such as energy efficiency, packet delivery ratio, latency, and duty cycle. We will analyze existing works on MAC protocols, using a common application scenario.

3. Application scenario

In order to understand the concept of IBSN better, an application scenario with implantable medical devices and sensors is explained. Consider an epileptic patient implanted with a deep-brain stimulator which stimulates the brain with electrical impulses in the event of seizure occurrences. It is possible to detect the occurrence of a seizure beforehand with symptoms that can be measured with implantable sensors such as an EEG sensor, blood flow sensor, and external sensors such as inertial accelerometers. To predict the onset of a seizure, the data from these sensors have to be processed in real time at the IBSN coordinator node, and control signals have to be sent to the implanted stimulator to suppress the seizure in real time. The wireless communication between sensor nodes and medical devices should be highly reliable with negligible delay in order to handle the situation flawlessly. Also, the occurrence of the symptoms is completely random, which means sensing should be done continuously, and occurrence of an event should be predicted locally by the sensor node. Processing the signal locally is out of the scope of this paper, but wireless communication should be efficient not only in terms of performance but also in terms of energy consumption to ensure a long-time operation. As an indication, the battery life time of implantable deep-brain stimulators is typically two to three years [20]. Few off-the-shelf stimulators are equipped with a rechargeable battery that can be recharged via an inductive link [20]. Having short-range communication such as a magnetic-induction system will not serve the purpose of communication with an off-body base station, hence a RF link with a coverage of at most ten meters and at least two meters is required. To ensure reliable RF communication, the underlying MAC protocol is crucial in terms of reliability and energy efficiency.

Table 1: Simulation parameter values

Parameter	Value	
Channel bandwidth	300	KHz
Reception current (main)	7	mA
Transmission current (main)	15	mA
Idle current (main)	3	mA
Sleep current	3	μA
Slot time	10	ms
Data rate	250	Kbps
Reception current (WUR)	8	μA
Transmission current (WUR)	1	mA
Data rate (WUR)	1	Kbps
Pathloss coefficient a	1.92	
Pathloss coefficient b	39.85	
Pathloss parameter σ_N	6.59	dB
Polarization parameter X_c	0.45	
Pathloss parameter d	10	m

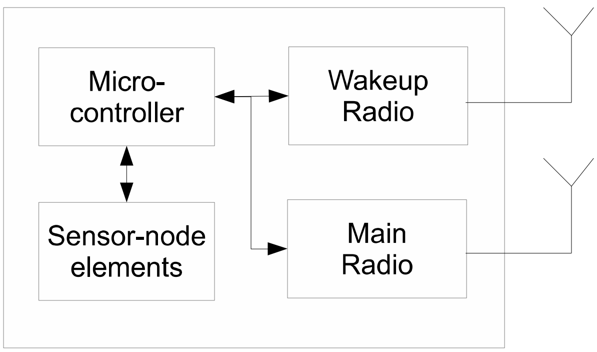

Figure 1: Common architecture of node with wake-up radio.

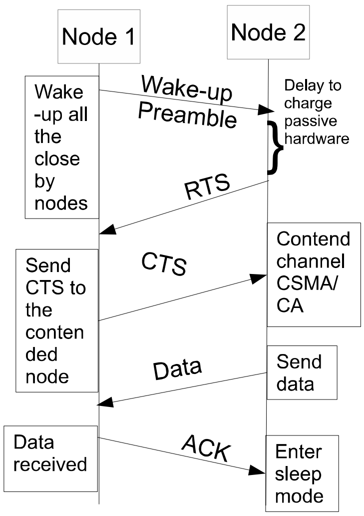

Figure 2: RTM scheme.

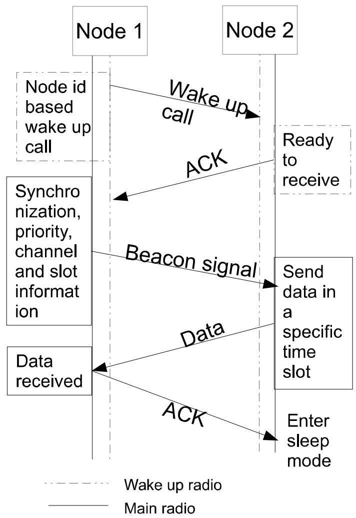

Figure 3: On-Demand MAC scheme

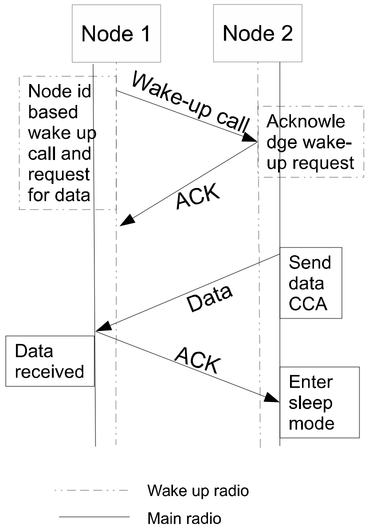

Figure 4: SCM-MAC scheme

4. Analysis of MAC protocols with WUR

In this paper, two WUR MAC protocols with a contention-based access mechanism and one with a contention-free access mechanism are analyzed. In this section these protocols are studied and analyzed based on their strengths and weaknesses, listed in Table 2. Because from literature a common network architecture was found to be a single-hop star topology containing 11 nodes [3][18], we used this topology for our simulations.

4.1. Radio Triggered sensor MAC

Radio Triggered sensor MAC (RTM) [21] has good potential for application in BSN as claimed by its authors. The wake-up feature is adapted using additional hardware consisting of a passive WUR sensor with a bandpass filter. The main radio and the micro-controller are triggered by the passive wake-up sensor upon an intended wake-up call (WUC). A sender uses the CSMA/CA contention mechanism for sending the WUC to other nodes. Upon gaining access to the medium, the sender sends out a wake-up preamble through the medium, which activates the passive WUR and triggers the main radio of the nodes. Communication is carried out using ReadyToSend/ClearToSend (RTS/CTS) as shown in Fig. 2. The RTS packet has information about the destination, which prevents other radios to overhear the data communication. The node to which the RTS is intended will send a CTS and complete the communication using an acknowledgement. Collision avoidance is incorporated using a Network Allocation Vector, which stores the time period for which the communication of the other node will take place. This information is available from data packets. By this, other nodes will know how long they should wait before they can access the medium. Back-off period and number of retries can be set easily in the protocol. In order to prevent energy wastage through overhearing, the nodes are put to sleep once they receive a RTS or CTS not intended for them.

4.2. OnDemand MAC

OnDemand MAC is a contention-free protocol, which uses WUR to trigger the main radio for data communication [22]. A wake-up schedule table is used for normal sensing operation where the central controller sends a WUC to the node and reads the data from the implanted node. A node can wake up the controller by sending a WUC for emergency medical events. Thus, the nodes in the network communicate on demand. The data communication is carried out by the main radio upon waking up in a TDMA-based access mechanism as shown in Fig. 3. The controller node of the network is responsible for slot allocation and channel allocation, in order to reduce the burden on the sensor nodes. Data communication starts only after the acknowledgement from the receiver and synchronization beacon from the controller. The data communication is then acknowledged, and the main radio is put to sleep.

Table 2: Strengths and weaknesses of selected MAC protocols

MAC	Strengths	Weaknesses
RTM [21]	simple WUR hardware; CSMA based, hence no clock drifts errors; suitable for P2P	reliability not guaranteed with CSMA/CA approach without GTS for emergency data; much energy is wasted in unnecessary wake-ups compared with TDMA
On Demand [22]	suitable for delay-sensitive scenarios (e.g. emergency data transfer); minimized collision resulting in reduced retransmissions and lower power consumption	synchronization beacons sent in both normal and emergency periods, lack of high-precision clocking in implanted nodes may lead to clock drift, hence very low reliability or large number of beacons, leading to lower effective throughput and more wasted bandwidth
SCM [10]	novel IBSN radio; low power consumption; larger coverage; low latency; high packet delivery ratio	no separate emergency data handling; simple collision handling may be problematic at higher data rates

4.3. SCM MAC

SCM MAC takes advantage of the Sub Carrier Modulation (SCM) WUR [10]. A very low operation power of 8μW is achieved for coverage distances of up till 30 meters. The SCM-MAC makes use of the simple OOK modulation for the WUC, encoding the node ID. The node ID will only wake up the main radio if the WUC is actually intended for it. The advantage of the node ID-based WUC will reduce the unwanted listening to data packets as it is in the case of RTM-MAC. The main radio uses Clear Channel Assessment (CCA) for data communication as shown in Fig. 4. Comparison with standard MAC without WUR, such as B-MAC and IEEE 802.15.4, has shown that SCM-MAC performs better in terms of better latency and high energy-efficiency [10]. This work is an example of state-of-the art WUR-based transceivers which can out-perform normal MAC protocols for use in IBSN.

5. Simulations

Simulations were performed in MATLAB by adapting the 802.15.6 channel mode for in-body communications [3]. The choice of using MATLAB over a network simulator is due to the availability of channel models and physical layer models for in-body communication scenarios. Discrete event simulation is repeated using inter-packet arrival time (IPAT) with a fixed data rate. Simulation was repeated for different values of IPAT, while observing parameters such as delay, power consumption, packet drop ratio and duty cycle. We perform evaluation based on these parameters in order to compare the effect of MAC protocols in in-body scenarios and these parameters will help us to understand the reliability and power consumption trade-off in different network conditions. IPAT is a commonly used parameter to evaluate network performance, as it is directly affected by changing network conditions. We modified the physical layer characteristics based on the recommendation of the IEEE 802.15 task group 6 proposal on the MICS band [3] and summarize them in Table 1. The same network architecture is used for all simulation runs. As an optimum for the chosen MAC protocols, a packet size of 50 bytes was used. CSMA-based protocols were implemented with a random back-off time. Other settings of the wake-up mechanism, such as wake-up interval, power consumption, and modulation techniques were chosen as proposed for each protocol in the referred literature.

5.1. Simulation results

Discrete event simulation in MATLAB has resulted in comparison of delay, packet delivery ratio, power consumption and duty cycle of three different varieties of MAC protocols with WUR as shown in Figs. 5–6.

Power consumption Power consumption is the total power consumed by the radio communication including the WUC and data communication. Upon evaluating it is observed that the power consumption of CSMA/CA based RTM-MAC is the highest for both low and high IPAT values. This is the effect of the unwanted listening of control packets by the nodes and unnecessary waking up of nodes for preambles. Also, the CSMA-based approach for data communication keeps the radio always switched on until the CTS is sent when data is completely transferred. The power consumption of TDMA-based on-demand MAC is the lowest, which is mainly due to the reduced number of control packets and intelligent control of synchronization by the On-Demand protocol. However, SCM-MAC is still in the acceptable region for moderate IPAT, when compared to the on-demand MAC. The lower power consumption of the SCM-MAC is due to the special chip that has been developed to operate in ultra-low power consumption on top of straightforward implementation of the CCA-based main radio. The main radio is completely switched off in the SCM-MAC until the intended WUC is decoded by the ultra-low power WUR. SCM-MAC is also interesting since the authors claim that it can operate with a coverage area of up to 30 meters at 8μA [10]. From this analysis, it is evident that simple passive hardware cannot be completely power efficient in the case of implants. Although the TDMA-based approach has an intelligent synchronization mechanism, in real hardware the clock drift will be influencing the power consumption of the sensor node. It can be clearly seen from the simulation results, that a WUR which can have an low power decoding option alongside the hybrid CSMA and guaranteed time slot is the best choice for power-efficient implantable sensor node communication.

Delay The delay in the sensor network is defined as the difference in time taken for a set of data that is sent to reach at the destination. Varying IPAT in different protocols will have influence on the delay due to the effect of preambles and control beacons sent alongside the data. In Fig. 8, three different protocols are compared in terms of delay. It is shown that the CSMA-based RTM has the highest delay with high IPAT. The delay is larger in RTM because at higher IPAT, the carrier sense overheads such as RTS, CTS and the wait time of passive wake-up for the data communication to complete. In the case of on-demand MAC, delay is almost constant for the data communication, because the only major delay is by wake-up and transmission of packets. The synchronization beacon is encoded in the packets which is also a reason for constant delay even though it reduces the effective throughput of the transmitted data. SCM-MAC on the other hand, still performs better than RTM, due to the node-id encoding in the WUC and also less unnecessary overhead such as passive activation like RTM. From the simulation analysis of the delay, it is evident that TDMA-based protocols are excellent in performance. The slot allocation for the channel access for each node is the crucial reason for constant delay. However, similar results can be achieved with CSMA-based protocols using GTS mechanisms.

Packet delivery ratio The packet delivery ratio (PDR) is the ratio of the total number of packets received at the receiver to the total number of packets generated at the sender. A 100% PDR means there is no loss of packets. In case of the in-body sensor network, IPAT can vary due to the highly varying physical properties of the human body. We evaluated the PDR for different IPAT to find the reliability of the different MAC protocols with WUR. As a result, we show that all protocols perform with high PDR at lower IPAT. However, as the IPAT increases the PDR of the protocols decreases. Out of the three MAC protocols chosen, SCM has a better delivery ratio, which is due to the reduced overheads and hence packets can be transferred in less time when compared to the TDMA-based approach. On-demand MAC has the worst PDR because the effective payload is reduced with longer preambles at higher IPAT. It is good to notice that on-demand MAC has a provision to send emergency traffic in higher priority. RTM has a better performance than on-demand MAC for similar reasons as SCM. However, the passive wake-up overheads and lack of device-specific wake-up causes RTM to have more packet loss at higher IPAT.

Duty cycle Duty cycle is the proportional duration for which the main radio is turned on in useful data communication. Higher IPAT will cause longer duty cycle. In RTM the CSMA-based access mechanism will have to sense the network randomly after every back-off time, which causes the radio to be turned on unnecessarily. In the case of on-demand MAC, the duty cycle is almost the same for different IPAT because of the fact the main radio is turned on only in pre-assigned time slots.

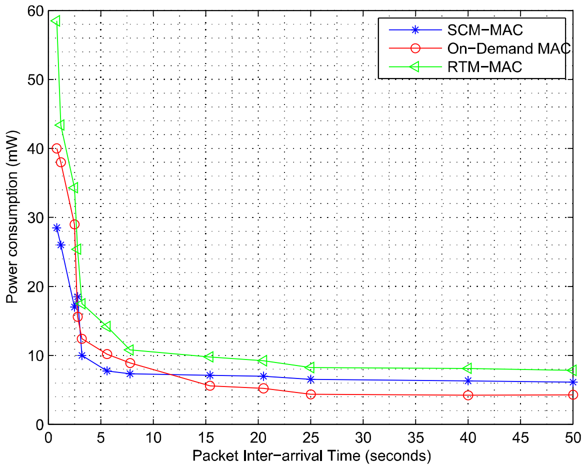

Figure 5: Effect of IPAT on power consumption

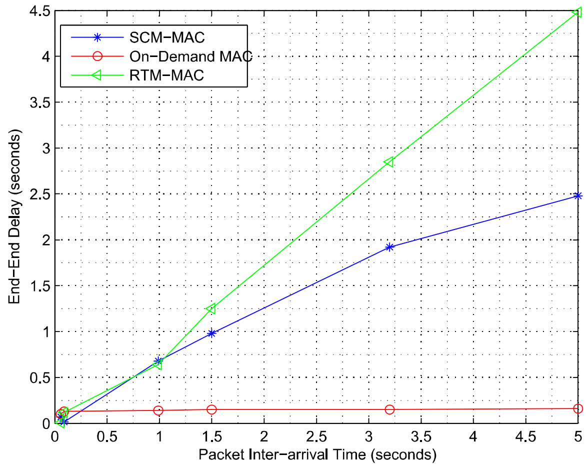

Figure 6: Effect of IPAT on End-to-End delay

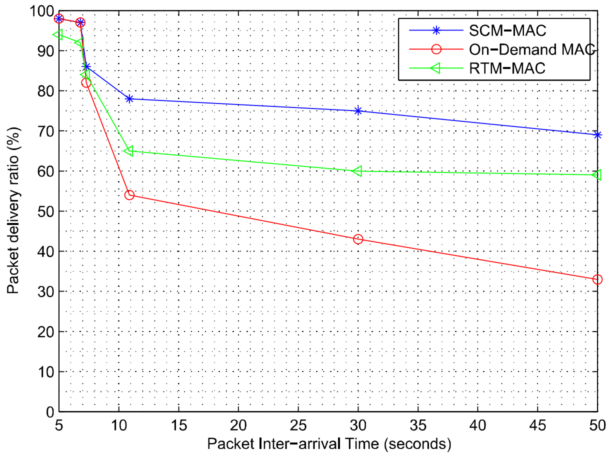

Figure 7: Effect of IPAT on packet delivery ratio

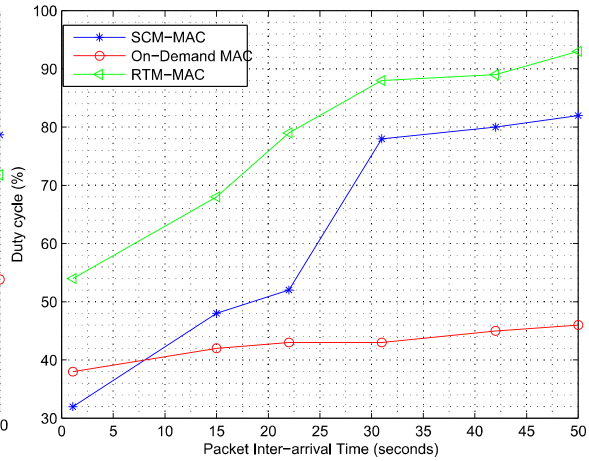

Figure 8: Effect of IPAT on End-to-End delay

6. Conclusion

In this paper we have analyzed three different WUR-MAC protocols based on their performance and access mechanisms. We discussed a simple application scenario of implantable body sensor network. Based on this scenario, simulations were performed to understand the effect of reliability and power consumption in a complex physical layer with unique conductivity and path loss effects. It is seen from the simulations that a hybrid access mechanism with contention-free access during emergency situations and contention-based access during the normal sensing process is the optimal choice for MAC protocols with a WUR. Even though it is claimed that TDMA is a good choice for in-body communication in terms of energy efficiency, the effect of clock drift will have serious complications. However, energy efficiency of the CSMA approach as implemented in SCM-MAC is similar to the TDMA approach. The WUR feature in SCM clearly removes the conventional problems of CSMA approaches such as idle-listening, over-hearing and packet-collision by implementing node-id encoded WUCs. Thus from the simulations it can be concluded that a wake-up based MAC protocol can perform reliably and energy-efficiently by adapting the advantages of both TDMA and CSMA approaches. At this point, the best choice of wake-up architecture is to use a dedicated WUR which can operate with several μW.

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